US Army Corps of Engineers
New England District

Conceptual Model of Tailings Piles at the Elizabeth Mine, South Strafford, VT

November, 2000

Interim Report Prepared For:

U.S. Army Corps of Engineers
New England District
Concord, Massachusetts

November 14, 2000

Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts
02140-2390

Contract No. DACW33-00-D-0002

Arthur D. Little Reference 70939

Arthur D Little

Table of Contents

Page

List of Tables

Table of Contents

Page

List of Figures

1.0 Introduction

1.1 Overview

This preliminary Conceptual Model report summarizes the efforts to date to develop an understanding of the surface and subsurface features of mine tailings piles at the Elizabeth Mine, located in South Strafford, Vermont. The intent of this document is to provide an overview of the tailings piles in a multidimensional view and establish base models for the surface water runoff and infiltration, groundwater flow, as well as the geotechnical stability of the tailings piles. Previous and ongoing studies have demonstrated that the tailings are a source of metals and acidity to Copperas Brook and the Ompomponoosuc River.

The conceptual model presented here is a work in progress and will be updated as new information is obtained. The model will form the foundation of the RI/FS scoping and the development of an EE/CA. It is expected that substantial improvements to the understanding of the site will occur as a result of the RI. This interim report presents a preliminary view of the key elements that make up the model and the current thinking behind each element. The conceptual model of the tailings is comprised of three elements:

- Surface water hydrology
- Subsurface (ground water) hydrology
- Structural stability

Figures and drawings contained in this report represent interim work products in the development of this preliminary model. The subsurface physical inter-relationships developed are based largely upon a geotechnical drilling program and field reconnaissance completed during the summer of 2000. Nine piezometer couplets were installed in and below the tailings material during that program. The borings were advanced to the base of the tailings and beyond in an effort to characterize tailings and natural geologic materials below the tailings. Short-screen piezometers were installed in each boring to characterize the pore pressures within the saturated zone of tailings and the sub-tailings materials.

At least four distinct source areas have been identified at the site, with respect to fate and transport of contaminants (Figure 1). Tailing Piles 1 (30 acres), 2 (5 acres), and 3 (6 acres) are located in the Copperas Brook watershed. Acid mine drainage (AMD), with elevated metals concentrations and high silt content, results from surface water and ground water flowing through these waste materials. The dry open cut (North Cut) may feed water into the mine workings and subsequently into the ground water regime. The flooded South Cut drains into the Lord Brook watershed. The mine workings have a point source discharge at a vent pipe located adjacent to the West Branch of the Ompompanoosuc River. Each source area eventually discharges to the West Branch of the Ompompanoosuc River. The groundwater contaminant migration pathways are not well understood.

EPA, at the request of VT DEC, evaluated the site for a time-critical removal action in the fall of 1999. A time-critical removal action was not initiated as a result of a lack of available funding, the complexity of the site, and public opposition. Subsequent to the determination by EPA not to proceed with the time critical removal action, EPA proposed a program that would include the implementation of a non-time-critical removal action (NTCRA) at the same time as the remedial investigation and feasibility study (RI/FS). Public opposition to this plan caused the Governor of Vermont to request that EPA delay NPL listing. Since February 2000, EPA has been involved in a program that addresses the community concerns and better explains the Superfund process. During the fall of 2000, EPA and the Community Advisory Group (CAG) reached consensus regarding a plan for the Site that includes a series of interim deliverables in advance of an engineering evaluation and cost analysis in support of a NTCRA. In September 2000, the CAG and Governor of Vermont submitted letters in support of the NPL listing. EPA's initial actions at the site have involved the planning and completion of a comprehensive surface water sampling program to assess the nature and extent of ecological risks due to acid mine drainage discharges into Copperas Brook and the Ompompanoosuc River.

1.2 Background

The Elizabeth Mine massive sulfide ore body was discovered along a ridge outside the town of South Strafford in 1793. The mine was initially worked for the sulfide mineral pyrrhotite to manufacture copperas, an iron sulfate, used in the past for a variety of purposes, including dyes and disinfectants. In 1830, Strafford Copperas Works was formed to exploit the site for copper. During the early mining operations, copper was smelted on-site. Underground mining began in the mid 1800's. The mine was worked intermittently from 1830 until the Great Depression in 1930. In 1942, the mine reopened in response to World War II and was operated by Vermont Copper Company until 1954. Appalachian Sulfides, Inc. operated the mine from 1954 to 1958. Most of the underground copper mining occurred from 1942 to 1958 (US Bureau of Mines, 1969) (Figure 2).

The principle tailings piles located at the site (TP-1 and 2) were generated through sulfide-rich ore milling operations between 1942 and 1958. At the outset of this latest period of mining, a "modern" flotation mill was constructed, where the ore was refined and the resulting concentrate was shipped off site to smelters on Long Island. The flotation mill was a major advancement in milling technology and allowed for efficient recovery of minerals from ore with small percentages of copper. By 1953 the milling operation consisted of three jaw crushers and screens to reduce the size of the ore, a ball mill to further reduce the ore particles to a powder, several flotation cells, where the powdered ore was placed in a frothing solution, and cleaners/thickeners to remove water and unwanted particles from the concentrate. In the flotation circuit, fine grained particles of the copper bearing mineral, chalcopyrite, were extracted. The remaining material was pumped to settling ponds via wooden troughs, resulting in the formation of Tailings Piles 1 and 2. Today, an orange iron-oxide rich "rind" covers the surface of TP-1 and 2 to a depth of 2 to 5 feet below the tailings surface. Below this oxide cap, black sulfide-rich tailings (anoxic) remain uniform to the base of each pile. The upper portion of these tailings piles is largely dry (unsaturated).

Tailings piles 1 and 2 are representative of a class of tailings impoundments referred to as "upstream tailings dams". Davies and Martin (2000) describe upstream tailings dams as those where the crest of the dam moves in a pond-ward direction relative to the initial "starter dam". In other words, the tailings impoundment starts with an earthen dam constructed at the toe of the proposed impoundment and tailings are deposited from down-slope (downstream) to up-slope (upstream). This approach results in wedge-shaped tailings pile, where the down-slope edge is topographically higher than the up-slope edge. By depositing tailings slurry at the downslope edge, coarser sandy material creates a dry beach at the down-slope edge and finer materials are transported by gravity and deposited in a settling pond within the upstream interior of the pile. Today, a decant tower for this interior pond can be observed on the surface of TP-1.

Upstream constructed tailings piles are very common in the mining industry, representing nearly 50% of all tailings impoundments constructed world-wide. Unfortunately, upstream construction also represents the most common failure mode in tailings dams; most major static/transient load induced liquefaction flow/slide events observed at tailings impoundments around the world have been associated with upstream construction (Davies and Martin, 2000).

Prior studies have described Tailings Pile 3, located adjacent to the North Cut, as an irregular pile of slag, waste rock, and roasted ore. Colorful piles of variably pyrolyzed sulfide ore give rise to a dramatic early industrial landscape, in an area thought to represent "heap leach" residues from the production of copperas (iron sulfate) throughout the 1800's. Bright orange-red hematite-rich piles represent thoroughly pyrolyzed massive sulfide. Yellow limonite and jarosite-rich material represents partially pyrolyzed ore material. Adjacent to the open cut, especially toward the southern end of the cut, low-sulfide content waste rock piles are mixed in with the sulfides used for copperas production. The material throughout TP-3 should not be referred to as "tailings"; however, the TP-3 nomenclature has meaning to most local citizens and site investigators. Therefore, for consistency, this area will continue to be referred to as Tailings Pile 3 in this report.

In general, Tailings Piles 1 and 2 are wedge-shaped, with the thickest sections situated along the down-slope, north-facing sides (Figures 3-7). TP-1 has a maximum thickness of approximately 110 feet; TP-2 has a maximum thickness of approximately 35 feet. TP-3 is very irregular in surface expression, with a thickness ranging from several feet to more than 40 feet. Directly underlying TP-1 and TP-2 is a thin layer of gravel/sand/debris representing the pre-tailings ground surface. This thin, water-bearing horizon appears to be no more than 2 to 3 feet in thickness; directly under this horizon is a glacial basal till sequence, measuring as much as 75 feet in thickness. The basal till rests directly on crystalline bedrock. Core samples of the till indicate that it is highly compact, dry, and comprised of rock fragments in a clay/silt matrix.

A volumetric analysis of TP-1 and 2 was completed by comparing the 1896 USGS topographic data to the recent (Spring, 2000) photogrammetry data. The 1896 data was significantly flawed, in that the elevations of the overburden material underlying the tailings did not correspond with the surface elevations of the 1896 data. Due to this discrepancy, the 1896 data was corrected using the borehole data as a guide. From this analysis, the total volume of the combined TP-1 and 2 piles was found to be approximately 2 million cubic yards (1,937,486 cu. yds.) (Figure 8).

Figure 1: Elizabeth Mine Surface Water Sampling Locations

Figure 2: Elizabeth Mine, South Strafford, VT - Cross-Section of Mine Workings

Figure 3: ElizabethMine, Strafford, VT – Map View of Tailings Pile 1, 2, & 3

Figure 4: Elizabeth Mine Conceptual Model – Cross - Section A-A"

Figure 5: Elizabeth Mine Conceptual Model – Cross Section A-A'

Figure 6: Elizabeth Mine Conceptual Model – Cross Section B-B’

Figure 7: Elizabeth Mine Conceptual Model – Cross – Section C-C'

Figure 8: Elizabeth Mine, Strafford, VT – Tailings Pile 1 & 2 Volume Estimation

2.0 Physical Setting

The Elizabeth Mine is located in the watershed of the West Branch of the Ompompanoosuc River, approximately 10 km upstream from its confluence with the East Branch of the Ompompanoosuc River near the Union Village dam. The Ompompanoosuc River empties into the Connecticut River downstream of the Union Village dam.

Upper Copperas Brook flows from the base of TP3, through a divide in TP2, onto the surface of TP1, where it enters a small pond (former settling pond for tailing fines). A decant tower diverts water from the surface of TP1 through concrete pipes to a discharge point at the northeast corner of the tailings pile. Waters from the discharge and from seeps run along the base of TP1 and coalesce to form “lower” Copperas Brook in the wooded areas and wetlands below the tailings.

The headwaters of the West Branch are underlain by the Devonian Waits River Formation, consisting of metamorphosed calcareous shales, shales, and minor quartzose limestones and dolostones, as well as the Devonian Standing Pond Volcanics, comprised of metamorphosed basalts. As the West Branch passes the mine site, it flows through the Devonian Gile Mountain Formation, the host rock of the copper deposit, which consists of metamorphosed black shales and graywackes, with lesser metamorphosed sandstones, calcareous shales, and diabase (Slack and others, 1993). High hardness values and alkalinity have been observed in the surface waters and can be attributed to the calcareous nature of the rock units upstream of the mine site in the West Branch of the Ompompanoosuc River.

The massive sulfide deposit at the Elizabeth Mine is a series of narrow, tabular ore shoots, dipping steeply to the east, plunging to the north, and extending intermittently over a strike length of more than a mile in a north-south direction. The deposit is characterized as a “Beshi-Type” massive sulfide, comprised largely of pyrrhotite with minor concentrations of chalcopyrite (copper-iron sulfide, 2-5%) and pyrite (iron sulfide). Similar deposits include Ducktown, Tennessee and Iron Mountain, California. The sulfide minerals were originally deposited in a deep-sea fumarolic setting, within a mixed sediment and volcanic depositional environment. Mid- to Early Paleozoic metamorphism of the sedimentary sequence resulted in a complex structural setting, where the original units have been tightly folded, overturned, and the sulfide minerals have been remobilized to the hinge zone of the dominant north-south (axis) folds. Within Vermont, similar massive sulfide deposits occur at Pike Hill and at the Ely Mine. Together, these three deposits have been referred to as the Vermont Copper Belt.

3.0 Surface Water Hydrology

This section of the report describes the current understanding of surface water hydrology, as it relates to tailings piles at the Elizabeth Mine. One of the most critical challenges for any future engineered solution to address tailings-related contamination, while preserving historical integrity, is the elimination (or substantial reduction) of water contact with tailings material. Surface water infiltration from storm events, snow melt, and Copperas Brook discharge to the surface of TP-1, results in a continuous source of metals to the surface water environment below (down-stream of) the tailings. To eliminate this ongoing source of contamination, surface water diversion around the tailings will be necessary (in addition to other remedies) under nearly all remedial scenarios.

As storm event flows are an important mechanism for contaminant loading from the tailings and waste material, a preliminary model of the storm water runoff at the site was developed. This model can be used not only to further site understanding as part of a conceptual model of the tailings and waste material, but also as a tool for design of remediation alternatives (e.g. design of channels to divert surface water flow around the contaminated area). The first step in the development of the storm water runoff model was the delineation of the Copperas Brook watershed, as well as the drainage basin contributing surface water flow into, through or over the tailings piles and waste material. Figure 9 shows the green outline of the Copperas Brook watershed. The watershed was first defined using a 1980 USGS topographic map with 20 ft contour intervals, and refined using the ADL 2000 survey data with 1 m contour intervals. The ADL survey data does not cover the entire watershed, and thus could not be used as the primary means of watershed delineation. All maps, figures, and spatial calculations of surface area provided in this section of the report were developed and calculated using AutoCAD Land Development software.

The watershed, or catchment basin of Copperas Brook at its confluence with the West Branch of the Ompompanoosuc River was determined to be 378 acres. The drainage basin of the contaminated areas (here defined as tailings piles 1, 2 and 3) were also calculated. The drainage basin of tailings pile 3 is approximately 17 acres (subject to the defined border of the waste rock), while the combined drainage basin of tailings piles 1 and 2 is 280 acres. However, approximately 21 acres of the 280 acre drainage basin only partially contributes flow to tailings piles 1. This 21 acre sub-basin drains into a channeled flow area which extends along the western side of TP 1. The water within this region does not contribute direct runoff to the tailings piles, but rather to the contaminated soils at the base of the western slope of TP 1.

3.1 TR-55 Storm Water Runoff Model

The method used for estimating direct runoff from a rainstorm was developed by the Soil Conservation Service* (SCS), based on studies of infiltration behavior for different types of soils under various land uses. The SCS developed computer programs incorporating the SCS methods for runoff prediction. For the initial model of direct storm runoff at the Elizabeth Mine, the SCS program Technical Release 55 (TR-55) was used and designed for modeling direct storm runoff from small watersheds for pre- and post-development scenarios.

The SCS method considers the following factors for estimation of runoff from a given rainfall event: hydrologic soil group, land cover type and condition, and pre-storm soil moisture condition. A distinct curve number (CN) is assigned to a given watershed (or sub-watershed), based on the above factors. The CN is used to estimate runoff in conjunction with the watershed's spatial information (size, shape, topography), and evaluation of flow types within the watershed. For watersheds that incorporate a number of different land covers and soil types that can be considered to have a uniform distribution across the watershed area, a composite CN (or weighted CN) can be computed for the watershed. This composite CN is an average of the various CNs which represent the watershed, weighted in proportion to surface area covered.

The SCS method assumes the unit hydrograph as its conceptual basis for estimating peak flows from rainfall events. Runoff movement through the watershed is characterized as one of three flow types: sheet flow, shallow concentrated flow, or open channel flow. In order to compute peak discharge, the time of concentration (Tc) is determined. The Tc is the amount of time required for rainfall runoff to travel from the most hydraulically remote point of the watershed to the reference point or watershed outlet. Flow velocity is calculated for each of the flow types, and used in conjunction with land cover type, and both length and slope of flow for computation of Tc. When a watershed encompasses multiple sub-watersheds, the travel time of runoff through downstream sub-watersheds is also computed.

TR-55 models runoff for different storm frequency events. Each storm frequency (e.g. 2-year storm event, 5-year, 10-year, etc) is considered to be a 24-hour rainfall event, in which the total rainfall amount is an input parameter, as is the rainfall distribution pattern for the given region in the U.S. (a map of rainfall distribution patterns and types found across the U.S. is provided in the TR-55 documentation). The storm event rainfall amounts used were extrapolated from a rainfall contour map from the *Atlas of Precipitation Extremes for the Northeastern U.S. and Southeastern Canada* obtained in March 2000 from Cornell University, and are the most current climate maps for the northeast U.S.

---

* The roles of the Soil Conservation Service have been incorporated into the Natural Resources Conservation Service (NRCS) organization. The NRCS is a current distributor of computerized models and publications developed by the SCS.

Peak discharge for a given storm frequency event is modeled in TR-55 by two methods: (1) graphical hydrograph, and (2) tabular hydrograph. The graphical hydrograph method considers the defined area as a homogeneous watershed for prediction of runoff and peak flow resulting from a given storm frequency event. Under the graphical method, a weighted curve number can still be determined, but the watershed does not require division into sub-watersheds. The tabular hydrograph method allows for the division of a watershed into sub-watersheds, each described with their own curve number, time of concentration, and travel time through downstream sub-watersheds. This information is then used to compute the change in runoff discharge over time at the point of interest (watershed outlet). From this output information, a stream runoff hydrograph can be developed for the storm event (excluding baseflow that is not considered by the model), and the peak flow can be determined.

3.2 Application of TR-55 to the Elizabeth Mine Site

Both the tabular and graphical methods were used to model the storm water runoff contribution to the tailings piles and mine waste rock at the Elizabeth Mine. As can be seen in Figure 10, the 280 acre drainage basin of the contaminated area was divided into 12 sub-watersheds based on topography, soil types, and the presence of natural or constructed channels. A composite curve number was estimated for each sub-watershed by calculating a weighted average (by surface area) of curve numbers determined for the various land cover types and hydrologic soil groups represented in the sub-watersheds. Land cover was determined through on-site observation as well as use of the ADL 2000 aerial photograph. The hydrologic soil groups were determined from soil maps provided by the SCS's *Soil Survey of Orange County, VT*, distributed by the Orange County NRCS office.

In addition, time of concentration (Tc) values were calculated for each of the 12 sub-watersheds. Tc values are calculated by estimating velocities associated with each flow type. For sheet flow, velocity is calculated as a function of length of flow and slope determined using the topographic maps of the site, and cover type determined through on-site observation and examination of the aerial photographs of the site. Shallow concentrated flow is also a function of slope and length of flow, and whether the shallow concentrated flow is on paved or unpaved terrain. Finally, the open channel flow velocity is determined using the Manning's equation. The bank-full stream measurements used in the Manning's equation were estimated and measured on-site, and the Manning's coefficient was estimated from standard tables. The CN, and Tc values developed as input parameters for each of the watersheds are listed below in Table 1:

Table 1: Sub-watershed Areas, and selected TR-55 Input Parameters

Sub-watersheds	Total Area (Acres)	Weighted Curve Number (CN)	Time of Conc. Tc (hr)
1	86.30	73	0.71
2	30.00	75	0.96
3	25.90	78	0.87
4	26.30	73	0.88
5	14.55	75	1.13
6	7.29	70	0.87
7	26.60	67	0.61
8	3.90	68	0.15
9	1.72	68	0.01
10	29.40	68	0.14
11	22.00	81	0.69
12	5.98	68	0.01

Sub-watershed 1 includes the entire drainage area (17 acres) of tailings pile 3, in addition to some areas down slope of tailings pile 3. The runoff discharged from sub-watersheds 1 through 7 flows directly onto tailings piles 1 and 2. Sub-watersheds 8, 9, 10 and 12 represent water falling directly on tailings piles 1 and 2. Thus, sub-watersheds 1 through 10 all contribute stormwater runoff into the pond on top of TP 1. Finally, sub-watershed 11 contributes water to the contaminated area running along the base of tailings pile 1 on the western side. This area is not part of the tailings pile, but is likely contaminated by the tailings material.

3.3 Graphical Hydrograph Method

For the graphical method, each of the sub-watersheds was modeled as a distinct watershed. The resulting output predicts the peak discharge from the base level of each sub-watershed, as well as the predicted runoff in inches averaged over the sub-watershed. This peak discharge considers only water input to the watershed during the storm event being modeled, and therefore does not incorporate base flow conditions. The peak storm discharges and runoff for the sub watershed areas are provided below:

Table 2: Output from TR-55 Graphical Hydrograph Method: Peak Flow discharged from base level of sub-watershed, and Runoff (in) from sub-watershed area.

		Watershed 1		Watershed 2		Watershed 3		Watershed 4	
Storm Freq. (yr)	24-Hr Rain (in)	Peak Flow (cfs)	Runoff (in)	Peak Flow (cfs)	Runoff (in)	Peak Flow (cfs)	Runoff (in)	Peak Flow (cfs)	Runoff (in)
2	2.40	24	0.5	9	0.6	10	0.7	7	0.6
5	2.97	43	0.8	14	0.9	16	1.1	12	0.9
10	3.39	58	1.1	19	1.2	21	1.4	17	1.2
25	4.24	94	1.7	30	1.8	32	2.1	26	1.8
50	5.08	133	2.3	42	2.5	43	2.8	37	2.4
100	5.65	161	2.8	50	3.0	51	3.3	45	2.9

		Watershed 5		Watershed 6		Watershed 7		Watershed 8	
Storm Freq. (yr)	24-Hr Rain (in)	Peak Flow (cfs)	Runoff (in)	Peak Flow (cfs)	Runoff (in)	Peak Flow (cfs)	Runoff (in)	Peak Flow (cfs)	Runoff (in)
2	2.40	4	0.6	1	0.4	4	0.3	1	0.3
5	2.97	6	0.9	3	0.7	9	0.6	3	0.6
10	3.39	8	1.2	4	0.9	13	0.8	4	0.8
25	4.24	13	1.8	6	1.5	23	1.3	7	1.4
50	5.08	18	2.5	9	2.1	34	1.9	10	1.9
100	5.65	22	3.0	11	2.5	42	2.3	12	2.4

		Watershed 9		Watershed 10		Watershed 11		Watershed 12	
Storm Freq. (yr)	24-Hr Rain (in)	Peak Flow (cfs)	Runoff (in)	Peak Flow (cfs)	Runoff (in)	Peak Flow (cfs)	Runoff (in)	Peak Flow (cfs)	Runoff (in)
2	2.40	2	0.3	11	0.3	12	0.9	7	0.3
5	2.97	3	0.6	22	0.6	19	1.3	10	0.6
10	3.39	4	0.8	32	0.8	24	1.6	13	0.8
25	4.24	6	1.4	53	1.4	35	2.3	20	1.4
50	5.08	8	1.9	77	1.9	47	3.1	27	1.9
100	5.65	9	2.4	95	2.4	55	3.6	33	2.4

From the runoff (inches) calculated by TR-55, the total volume of runoff from a given storm event can be estimated. Table 3, below, provides estimates of the total runoff discharged from each sub-watershed for each of the storm frequency events modeled, in addition to the total cumulative runoff of all 13 sub-watersheds. This is an estimate of the volume of direct runoff water which contacts the site's contaminated areas during each of the storm frequencies modeled:

Table 3: Runoff Volume (acre feet) discharged from individual sub-watersheds for various storm frequency events.

		Estimated Runoff Volume (acre-ft) for each sub-Watershed												Total Volume	
Storm Freq. (yr)	24-Hr Rain (in)	1	2	3	4	5	6	7	8	9	10	11	12	Acre-Ft	Cubic Feet
2	2.40	3.60	1.50	1.51	1.32	0.73	0.24	0.67	0.10	0.04	0.68	1.65	0.15	**12.17**	**5.E+05**
5	2.97	5.75	2.25	2.37	1.97	1.09	0.43	1.33	0.20	0.09	1.36	2.38	0.30	**19.51**	**9.E+05**
10	3.39	7.91	3.00	3.02	2.63	1.46	0.55	1.77	0.26	0.11	1.81	2.93	0.40	**25.85**	**1.E+06**
25	4.24	12.23	4.50	4.53	3.95	2.18	0.91	2.88	0.46	0.20	3.16	4.22	0.70	**39.91**	**2.E+06**
50	5.08	16.54	6.25	6.04	5.26	3.03	1.28	4.21	0.62	0.27	4.29	5.68	0.95	**54.42**	**2.E+06**
100	5.65	20.14	7.50	7.12	6.36	3.64	1.52	5.10	0.78	0.34	5.42	6.60	1.20	**65.71**	**3.E+06**

3.4 Tabular Hydrograph Method

In addition to modeling each sub-watershed individually using TR-55's graphical hydrograph method, the tabular hydrograph method was also used to estimate storm water hydrographs for the drainage basin of tailings piles 1 and 2. Storm water hydrographs represent the change in stream flow as a result of a storm event. The hydrograph charts begin with a storm water stream flow of zero, because at the start of the storm there is no contribution from storm water runoff. This does not mean that the stream is dry, as there would likely be base flow from groundwater contributions to the storm. The discharge in the storm water hydrograph represents only contributions to the stream from the storm event being modeled. Sub-watersheds 1 through 10 were used in the model to predict runoff into the pond located on top of tailings pile 1. Both sub-watersheds 11 and 12 were excluded from this model as they do not contribute runoff to the pond on the tailings pile.

Due to a lack of information at this stage of investigation, the entire Copperas Brook watershed (with the base level being the confluence with the West Branch of the Ompompanoosuc River) could not be modeled. Unknowns at this time include the following: (1) change in discharge rates into the decant tower located at the northern end of the pond on tailings pile 1 based on storm flow events, (2) the integrity of the decant tower through the tailings pile, and (3) the rates of groundwater flow of water through the tailings pile (and exiting the tailings as groundwater seeps at the base of tailings pile 1). Due to lack of information on the integrity of the decant towers, the amount of water that would remain runoff vs. that which would become groundwater flow through the tailings (and therefore no longer be classified as runoff) is unknown.

A chart of the storm water stream hydrographs for runoff discharge into the tailings pond for 10-year, 25-year and 100-year storm events is provided in Figure 11.

The "Discharge into Pond" along the vertical axis indicates the accumulated discharge into the pond for all 10 sub-watersheds; i.e. the sum of discharges from all 10 sub-watersheds (at any given time after storm start) that contribute storm water to the pond on top of TP 1. "Time" on the horizontal axis shows time passed over the course of the 24 hour period during which the storm event occurs. The stream hydrograph results of the tabular hydrograph method are of limited use. However, the estimates of peak flow, which can be inferred from the stream hydrograph, can be useful for determining design parameters. In the case of modeling current conditions at the site, the estimates of total runoff (inches) for a given storm event is the most useful result of the model as it provides insight into both total runoff flows, and the amount of runoff contacting contaminated areas for various storm events.

The peak flow into the pond on top of tailings pile 1 for each of the storm frequencies modeled is provided in the Table below:

Table 4 : Peak flow into the pond on tailings pile 1 (accumulated from all points of runoff discharge from the 10 sub-watersheds contributing).

Storm Freq. (yr)	24-Hr Rain (in)	Peak Flow (cfs)
2	2.40	54
5	2.97	100
10	3.39	142
25	4.24	238
50	5.08	359
100	5.65	450

This peak flow represents the direct runoff from the storm event (or antecedent moisture conditions of the storm event), but does not include the base flow of the stream.

3.5 Preliminary Proposal of Diversion Channels

In order to gain an understanding of the potential effectiveness of constructing channels around Tailings Piles 1 and 2 for diversion of surface water flow from entering the waste material, a placement option for two diversion channels (one on each side of tailings piles 1 and 2) was developed. The diversion channel placement was chosen based on the following factors:

- favorable (downward sloping) existing topography, using the detailed surface topography of 1 meter topographic contour intervals
- avoidance of the tailings piles while remaining in close proximity to the tailings to divert maximum surface water from the "clean" portions of the watershed from entering the contaminated area

- existing channeled flow
- avoidance of existing buildings and historic ruins

Figure 12 provides a view of the proposed placement of the diversion channels, while Figure 13 shows the vertical profile of each diversion channel. There is a downward vertical trend for each of the proposed diversion channels, indicating that they are topographically feasible and reasonable to construct. Finally, Figure 14 shows the portion of the watershed contributing storm water flow (or surface water runoff) to tailings piles 1 and 2 after implementation of proposed diversion channels.

Implementation of diversion channels in the proposed locations has the potential to divert up to 90% of the storm water runoff currently contributing to the contaminated area for the design flow storm (and any storms less than the design storm frequency). That is, up to 90% of the storm water flows which currently flow over, through or into the tailings pile, would be diverted and thereby prevented from contacting contaminated areas by construction of diversion channels.

3.6 TR-55 Model of Post-Remediation Scenario

TR-55 was then used to predict peak flows in each of the diversion channels for various storm events. In order to model a post-remediation scenario, the following assumptions were made:

- Consolidation of the tailings and waste rock such that the waste material of TP 3 is moved onto TP 1 and 2, leaving bedrock in the former TP 3 area. Soil of hydrologic group A/B is placed over the former TP 3, and the surface is vegetated with native grasses for erosion control
- TP 1 and 2 (as well as the material from TP 3) are graded to a 3% slope, such that runoff will have equal contributions to each of the two diversion channels; the waste material is capped following this 3% slope, covered with topsoil of hydrologic soil group A/B, and then vegetated with native grasses
- All of the water from the upper part of the watershed is channeled into the eastern diversion channel (Channel 2); this is mostly to minimize construction and disturbance in the area near the historic mining ruins on the western side of TP 1

The resulting TR-55 model output is shown on the following page:

Table 5: TR-55 Peak flow estimates for West East diversion channels.

Storm Freq. (yr)	24-Hr Rain (in)	Channel 1 (West) Peak Flow (cfs)	Channel 1 (West) Runoff (in)	Channel 2 (East) Peak Flow (cfs)	Channel 2 (East) Runoff (in)
2	2.40	5	0.2	24	0.3
5	2.97	14	0.5	54	0.6
10	3.39	23	0.7	81	0.8
25	4.24	43	1.1	141	1.3
50	5.08	67	1.6	210	1.9
100	5.65	84	2.0	261	2.3

These predictions of peak flow were next used for the initial sizing of the two diversion channels. Diversion channels were sized to accommodate storm flow from a 10-year storm event. Since TR-55 and other modeling systems based on empirical estimates tend to largely overestimate flow, these flows were assumed to provide a sufficient design safety factor.

The assumptions used for design of the channels:

- Rip-rap lined channel with trapezoidal cross-section
- 1:1.5 side slopes for trapezoidal cross-section (recommended slope for lined channels by the Bureau of Reclamation) (Gupta, 1995)
- Trapezoidal base width should be less than or equal to the water depth; assume width to depth ratio of 0.8.
- Average slope of West channel (1) is 6%, and that of the East channel (2) is 2.5%
- Manning's n for both channels is 0.027 (mid range for rip-rap lined channels)
- Minimum velocity in the channel is 2 ft/s = 0.61 m/s

The channel dimensions are calculated using the following relationships:

$$AR^{2/3} = \frac{Qn}{S^{1/2}}$$

where: A = cross-sectional area of channel
R = hydraulic radius of channel = A/P, where P = wetted perimeter of channel
Q = discharge or peak flow
n = Manning's coefficient
S = channel slope

$$\frac{b}{y} = 0.8$$

where: b = base of trapezoidal cross-section
y = depth of water in channel

$$A = by + 1.5y^2$$

This final relationship is based on the 1:1.5 side slope requirements for the channel.

The resulting dimensions and parameters for the respective channels are provided below in Table :

Table 6: Initial Sizing and Design Parameters for Diversion Channels.

	Q (cfs)	y (ft)	b (ft)	A (sq. ft)	V (ft/s)
Channel 1 (West)	23	1.04	0.84	2.54	9.02
Channel 2 (East)	81	1.98	1.59	9.08	8.89

3.7 Discussion and Conclusions on TR-55 Storm Water Modeling

The TR-55 model of current conditions on-site may be an overestimate of peak runoff flows, and of total runoff at the site. This is due, in part, to the inherent TR-55 modeling approach and associated assumptions. In addition, it is due to the curve numbers developed to represent the 12 sub-watersheds. The *Soil Survey of Orange County, VT*, provides information on the soil types present at the site, including their classification for hydrologic behavior. Conservative estimates of these soils were used; that is, where more than one soil was represented in a sub-watershed, the soil with the largest runoff generating capacity was chosen to represent the sub-watershed (provided that it represented a substantial portion of the given sub-watershed, e.g. roughly 40% or more). Most of the soils represented in the Copperas Brook watershed are of hydrologic soil group C or C/D, both of which lead to greater predictions of total runoff, as these soils contain more clays and allow for less infiltration than soils of A or B type. In the model presented above, if hydrologic group C soil is determined to overestimate runoff to an unreasonable extent in the future, changing the soil types and the resulting curve numbers is a straightforward process. In short, the model can be easily adjusted in the future to account for new information on the site.

The most important component of output from the TR-55 model of current site conditions is the estimate of runoff for each of the sub-watersheds for given storm events. Using the areas of the sub-watersheds, the total volume of storm water input to the contaminated area can be estimated for any given storm event. This provides an estimate of the total storm runoff that has potential to become contaminated by the tailings and waste rock at the site for any given storm event.

This model of storm water runoff provides a framework for future development of surface water runoff modeling at the Elizabeth Mine. Although the model is preliminary, it provides important insights into existing hydrology and behavior of surface water at the Elizabeth Mine. In addition, as is displayed by the preliminary proposal of diversion channels, the model provides a tool for analysis and design of remediation options.

Future work may include using a more robust model that HEC HMS has developed and currently a standard tool used by the ACE. This model is considered a more robust model for precipitation-runoff processes and may be used later for more accurate predictions for design of remediation alternatives as well as prediction of effectiveness.

Figure 9: Copperas Brook Watershed & Drainage Basin of Tailings COE – Elizabeth Mine, Strafford, Vermont

Figure 10: Subareas for TR – 55 Model COE – Elizabeth Mine Straford, Vermont

Figure 11: Storm Hydrographs developed from TR-55 Tabular Hydrograph Model

Figure 12: Proposed Diversion Channels – Elizabeth Mine Strafford, Vermont

Figure 13: **Vertical Profiles of Proposed Diversion Channels – COE - Elizabeth Mine Strafford, Vermont**

Figure 14: Copperas Brook Watershed & Drainage Basin of Tailings with Proposed Diversion Channels – COE – Elizabeth Mine Strafford, Vermont

4.0 Groundwater Hydrology

Understanding the nature of ground water flow below and around the tailings piles is an important aspect of the investigation and design process. Groundwater within the tailings material in TP-1 and 2 is likely a result of two components: surface water infiltration and infiltration from groundwater perched upon the tailings/till interface. At present Groundwater volumes of infiltration and transport related to the decant tower and the irregular transmissive geologic units below the tailings is not well documented. Further investigation is necessary to evaluate the significance of these features. Based on the results of the geotechnical boring program, the relative contribution from the surrounding ground water is likely minimal, while the surface water infiltration likely represents the dominant recharge mechanism. Understanding this relationship in greater detail is essential to developing a balanced groundwater model as well as a water control strategy for the final remedy. Currently, ground water seeps are observed in a number of locations at the toe of TP-1, with a lesser amount at the toe of TP-2. Ground water discharges at the surface near the toe of TP-3, forming the headwaters of Copperas Brook.

To evaluate the nature of ground water flow and distribution within the tailings, 9 piezometer clusters were installed through the tailings in July/August, 2000 (Figure 15). The piezometers have since been developed and allowed to equilibrate with existing pore pressures. Ground water measurements were then collected and are shown in Table 7. The only measurements collected to date reflect summer conditions, although the summer of 2000 in New England was wetter than usual. As shown in the table, groundwater elevations did not fluctuate considerably between the sampling events. Out of the nine piezometers, there was one significant variance at PZ-4 situated in the middle of TP1. Groundwater levels in PZ-4 dropped 5.87 feet between the first two measurement events, but is not considered a valid comparison. This anomaly is likely attributed to equilibration of the water level after installation of piezometers. More data is necessary to evaluate the seasonal impact on the groundwater from precipitation and infiltration.

Tailings material in TP-1 and 2 is generally characterized as a fine sand (Figure 16). The upper 3 to 5 feet of the tailings piles is highly oxidized and orange/tan in color. Below this oxidized zone, the tailings takes the form of a hard black anoxic silt/fine sand. There does not appear to be any vertical differentiation throughout the pile, although a thin clay-rich accumulation layer was noted in several borings at a depth of several inches to one foot below the tailings surface.

Table 7: Depth to Water Measurements in Tailings Material from August to October.

Piezometer	Depth to Water (ft) 8/10/00	Depth to Water (ft) 9/28/00	Change (+/- ft)	Depth to Water (ft) 10/17/00	Change (+/- ft)
PZ1A	10.36	10.76	-0.4	10.83	-0.07
PZ1B	5.85	6.27	-0.42	6.53	-0.26
PZ2A	92.52	91.62	0.9	91.5	0.12
PZ2B	93.1	92.42	0.68	92.47	-0.05
PZ3A	64.74	64.69	0.05	64.8	-0.11
PZ3B	78.87	78.5	0.37	78.6	-0.1
PZ4A	39.72	45.59	-5.87	45.6	-0.01
PZ4B	46.18	45.92	0.26	46.05	-0.13
PZ5A	13.62	15.38	-1.76	15.92	-0.54
PZ5B	16.73	17.89	-1.16	18.55	-0.66
PZ6B	8.02	8.71	-0.69	8.88	-0.17
PZ7A	10	10.44	-0.44	10.55	-0.11
PZ7B	10.6	10.98	-0.38	11	-0.02
PZ7C	48.97	49.6	-0.63	49.78	-0.18
PZ8A	3.44	3.62	-0.18	3.49	0.13
PZ8B	3.55	3.75	-0.2	3.49	0.26
PZ9A	16.83	17.85	-1.02	18.31	-0.46
PZ9B	18.15	18.45	-0.3	18.7	-0.25

Measurements within and below TP-1 and TP-2 indicate that ground water flow is toward the north-northwest, generally following the pre-tailings surface topography (Figure 17). Nested piezometer couplets indicate that there is a slight downward vertical gradient throughout TP-1 and TP-2 (Figure 15). Hydraulic conductivity has not been determined at this point; tailings porosity is likely on the order of 20%. The information gathered to date indicates that the basal till underlying the tailings piles (1 and 2) is a low-yield, nearly impervious geologic material of considerable thickness overlying bedrock. The thin, irregular water-bearing unit between the tailings and till does not appear to be a significant ground water resource, but it may be a preferred hydraulic pathway for minor lateral flow and recharge to the base of the tailings. The downward vertical gradient present during summer months suggests, however, that any recharge to the tailings from below is likely limited. Future efforts to manage ground water within and around the tailings will address this flow pathway in greater detail.

Groundwater recharge to the tailings in TP-1 and 2 is principally from rainfall, snow melt, and (importantly) surface water discharge from the upper portion of the watershed. A concrete diversion culvert, once situated below TP-2, has completely eroded, resulting in direct discharge of the upper reach of Copperas Brook onto the surface of TP-1. This has resulted in a year-round surface pond, measuring 1 to 2 acres, on the top of TP-1. A similar concrete stand-pipe remains in place to channel Copperas Brook flow from the pond, below TP-1, back into a natural drainage channel at the foot of TP-1.

A single clustered piezometer situated in TP-3 indicates the presence of a near surface unconfined water-bearing horizon above the bedrock and a second saturated zone within the highly fractured bedrock. Depth to bedrock at this location is approximately 12 feet below ground surface. The piezometer cluster indicates that a significant upward vertical gradient is present between the two water-bearing zones in this area. Recharge to the bedrock aquifer is likely through a combination of precipitation/infiltration and flooded underground workings below the North Cut. The horizontal gradient, while not known at this time, is likely significant and follows the natural topography.

Figure 15: Elizabeth Mine, Strafford, VT – Map View of Tailings Pile 1, 2, &3

Figure 16: Elizabeth Mine Cores Size Fraction Analysis of Surface Material

Figure 17: Level of Stability of Tailings Pile 1

5.0 Geotechnical Stability of Tailings Piles

The Elizabeth Mine project presents a diverse range of geotechnical issues. The most prominent relate to slope stability and closure considerations.

Table 8 presents Performance Criteria under development for the geotechnical issues at the Elizabeth Mine. The Performance Criteria consists of qualitative and quantitative parameters selected to reflect critical aspects of performance. The Performance Criteria helps achieve the following:

- Establish possible failure mechanisms
- Determine the consequences of failure
- Select an acceptable level of risk
- Establish criteria of performance
- Ensure that the criteria meet appropriate legal requirements and accepted standards of practice

Lack of clear performance criteria early in the design of a project could result in either an excessively conservative design or an unsafe design.

Figure 17 presents a Stress Path portrayal for Tailings Pile 1. The Stress Path Method (Lambe, 1967; Lambe & Marr, 1979; Lambe & Silva, 1998) is most useful in analyzing earth structures. The Stress Path Method provides a framework to apply the Effective Stress Principle to:

- Elucidate a geotechnical problem
- Rationally solve a problem
- Portray a solution

The Stress Path Method uses laboratory and field data to obtain the stress path of average stresses in a field situation for past, present, and future conditions. To evaluate stability using the Stress Path method, the engineer plots the field Total Stress Path (TSP) and field Effective Stress Path (ESP). For stability assessments we find it convenient to use the average σ_n vs. τ TSP and the corresponding $\bar{\sigma}_n$ vs. τ ESP. Whenever the ESP reaches the $\bar{\sigma}_{nf}$ vs. τ_{ff} strength envelope determined from field or laboratory tests, failure occurs. Figure 17 shows a stress path plot used to evaluate the stability of Tailings Pile 1.

Table 8 lists the components of a stability analysis, the goal of which is to determine the Factor of Safety [FS]. For each event there is a specific path to failure, analysis, testing, etc., which must be considered in order to make a rational stability analysis. The stability analysis should model the events experienced or predicted in the field structure. At a minimum, one must evaluate the implications to the assessment of the level of stability from discrepancies between field conditions and the conditions used for the stability analysis.

From Figure 17 we see that although the slopes of TP1 appear stable in the field, the average effective stress point lies in close proximity to the failure envelope. Predictable events such as the 100 year storm (Stage Sc) or a mild earthquake (Stage Ec) can bring the ESP over the strength envelope, i.e. cause failure. Any regrading (Stage R) must ensure an adequate margin of safety under these conditions (Stages Sr and Er). Similar assessment must be made for the rock slopes beneath TP3. The minimum slope angle for the final grade, based on this preliminary assessment is 3:1.

Components of Stability Analysis

Table 8: Performance Criteria, Elizabeth Mine, Vermont

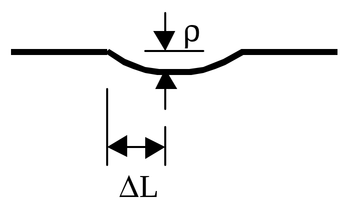
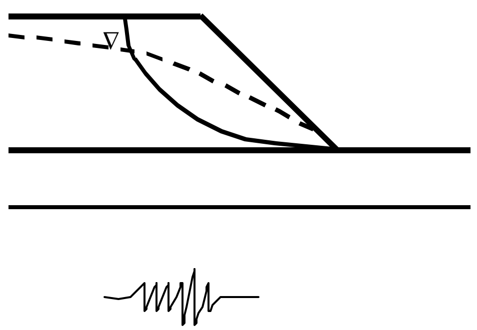
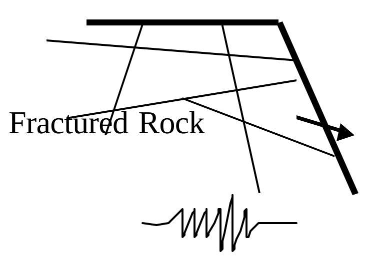
	PERFORMANCE ASPECT	MALFUNCTION MODES	PERFORMANCE CRITERIA	COMMENTS
FORCE-DEFORMATION	Settlements 	Excessive differential settlements result in surface ponds, increasing infiltration of surface water and maintenance requirements.	$\rho/\Delta L \leq 1/100$	Settlements difficult to predict accurately. However, since the tailings are very sandy, most of the settlements may take place in a very short time. An inspection and maintenance program can be implemented to ensure that the performance criterion is satisfied. ρ = total settlement ΔL = distance between adjacent measuring points $\rho/\Delta L$ = angular distortion
STABILITY	Stability of Tailings Slope 	• Normal Conditions: steep slope angle results in shear slide. • Storm: High pore water pressure reduces effective stresses. A shear slide results. • Earthquake: Vibrations induced by earthquake increase pore water pressure and thus reduce the effective stresses, earthquake loads increase driving forces. A shear slide results. If effective stresses approach zero, liquefaction occurs. Landslides expose fresh sulfides and result in increasing contamination through acid generation and metals release.	FS ≥ 1.5 (Normal conditions) FS ≥ 1.3 (100 year storm) FS ≥ 1.2 (Seismic)	Stability analyses for different conditions need to be conducted and the tailings slope may need to be regraded or stabilized so that the performance criteria are satisfied. It is important to conduct detailed field investigation to determine the geotechnical properties of the tailings. FS = Factor of Safety = $\frac{s_a}{\tau_a}$ where s_a = average strength along the potential sliding surface; τ_a = average shear stress along the same surface.
	Stability of Rock Slope 	• Existing discontinuities (fractures, joints) in the rock mass may form unstable rock wedges. • Earthquake induces dynamic forces that may trigger instability of rock wedges normally stable under static conditions.	FS ≥ 1.5 (Normal conditions) FS ≥ 1.2 (Seismic)	Stability analyses for different conditions need to be conducted and the rock slope may need to be stabilized so that the performance criteria are satisfied. It is important to conduct a detailed discontinuity sampling at the site so that the information on the orientation and persistence of discontinuities can be obtained and then used to evaluate the safety of rock slopes. FS = Factor of Safety = $\frac{s_a}{\tau_a}$.

Table 8: Performance Criteria, Elizabeth Mine, Vermont (Continued)

	PERFORMANCE ASPECT	MALFUNCTION MODES	PERFORMANCE CRITERIA	COMMENTS
FLOW	Surface Flow	Surface runoff infiltrates tailings and transports contaminants.	Limit runoff to precipitation fallings directly on tailings piles	Upper Copperas Brook Creek should be diverted away from the tailings piles.
	Subsurface Flow		Flow off property ≤ 100 gpm	Subsurface flow through the tailings region should be controlled.
	Surface Erosion	Erosion transports contaminants.	Maximum gully size: $l \leq 10$ m $w \leq 0.5$ m d ≤ 0.3 m	Consider using erosion control geotextiles to minimize maintenance activities and cost.
	Subsurface Erosion	Erosion transports contaminants and lead instability of slopes.	FS against piping ≥ 1.4	Consider using erosion control geotextiles and geotextile filters to minimize maintenance activities and cost.
	Flow Quality	Contaminants in the flow water exceed required level.		
MISCELLANEOUS	Vegetation	Roots of trees damage geotextiles and drainage layers.	Limit vegetation to surface grasses and other ground covers.	

6.0 References

Slack, JF, Offield, TW, Shanks, WC, III, and Woodruff, LG, 1993, Besshi-type Massive Sulfide Deposits of the Vermont Copper Belt, in JF Slack and TW Offield, eds., Selected mineral deposits of Vermont and the Adirondack Mountains, New York, II. Besshi-type Massive Sulfide Deposits of the Vermont Copper Belt: Society of Economic Geologist Guidebook Series, v. 17, p. 32-73.

Davies, M.P. & Martin, T.E., Tailings and Mine Waste 2000 Balkema. Preceedigs of the Seventh International Conference on Tailings and Mine Waste 2000/Fort Collins/Colorado/USA/23-26/January 2000. Pgs. 3-17.